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Evaluation of conventional and Equivalent Mortar Volume mix design methods for recycled aggregate concrete

Emmanuel E. Anike, Messaoud Saidani, Eshmaiel Ganjian, Mark Tyrer & Adegoke O. Olubanwo

Abstract

The use of recycled aggregate concrete (RAC) is undoubtedly on the increase and further research is required for more appropriate mix design methods. This paper presents the result of investigations into the mix design of RAC. The study examined experimentally two conventional and one unconventional mix design methods. The conventional methods include the absolute volume approach according to the American Concrete Institute (ACI) standard and the Department of Environment (DoE) concrete mix design method given by the British specification. The unconventional method is a new technique dubbed "Equivalent mortar volume (EMV)" method developed to incorporate both fine and coarse recycled aggregates for RAC production. A total of four mixes were designed as follows: (i) natural aggregate concrete (NAC) regarded as the reference mix using the ACI guide, (ii) RAC using the ACI guide, (iii) RAC using the DoE guide and (iv) blended aggregate concrete (BAC) using the EMV guide. Fresh concrete properties were tested, and twenty concrete cubes and eighteen cylinders were produced accordingly and tested after curing by water immersion for density, compressive strength, tensile splitting strength and water absorption. The results showed that the EMV mix design method used significantly lesser amount of cement to achieve a RAC of higher strength than those obtained from its comparable conventional methods even with original natural aggregates. This is the first work on mix design of RAC incorporating both coarse and fine crushed concrete aggregates carried out using the EMV method. This research highlights that the ACI and DoE mix design method guides should be reviewed and amended appropriately, before adopting them for RAC mix design.

Keywords: Mix design, Equivalent mortar volume, Recycled concrete aggregate, Blended aggregate, Compressive strength

1. Introduction

Concrete is an essential construction material. However, the production of concrete causes huge environmental challenges arising from aggregates and cement requirements [1,2]. Consequently, the continuous exploitation of natural aggregate (NA) exposes us all to dangers associated with climate change and resource depletion. Similarly, the obsolete nature of early structures and the drive to attain modern designs and specifications have also led to demolition of many existing concrete structures. This is aggravated by the incidences of natural disaster like tsunami and earthquake [2], contributing to the enormous amount of construction and demolition waste (CDW) generated worldwide. Hence, the world is confronted with the challenge of how best to manage the generated CDW as well as protect the diminishing natural resources. In attempts to alleviate these problems, studies have shown that recycling concrete waste into aggregate to be used in new concrete, remains a viable solution. Notably, some of the concrete rubble is from structures of moderate or high strength reinforced or precast concretes [3] and this creates opportunities for their re-use in concrete manufacture.

Undoubtedly, remarkable progress has been made and there is a general perception that the presence of dry mortar in RA is responsible for its reduced performance in concrete relative to NA [4,5]. It should be noted that the amount of dry mortar present in RA depends on the concrete grades from which the RA is sourced [6]. In their "Cement paste content and water absorption of recycled concrete coarse aggregates" work, Belin et al. [6] showed that the RA obtained by crushing lower-grade concretes has its adhering cement paste mostly separated without any special treatments. This is simply because the low strength pastes easily break-up upon crushing. But the components of higher-grade concretes remain attached to the homogeneous fragments produced after the crushing process. Of course, these scenarios have their unique challenges and impact in concrete. Nevertheless, Etxeberria et al. [7] maintained that none of the results from the previous studies proves RA unfit for structural applications. Thus, the problem with RA is not intrinsic [8] but lies in the mix design of its concrete. There is no globally accepted mix design for recycled aggregate concrete (RAC) [9]. This is exacerbated by the variability in the properties of RA [10,11].

The design of RAC mix requires additional water to obtain similar workability relative to NAC and such alteration may influence the mechanical properties of RAC [12]. However, the use of water-reducing admixtures (superplasticizers) helps to achieve the desired workability of fresh concrete with no negative effects on the properties of the hardened concrete. The reduced workability of RAC is linked with the high porous structure of RA [13,14]. This porous nature is said to be responsible for the inferiority of RAC compared to NAC, in terms of concrete microstructure [15]. At microstructure level, Gómez-Soberón [16] noted that the porosity of RAC increases with RA substitution ratio and this leads to reduced strength [16,17]. The mechanical properties of RAC have been found to be affected by both quantity and quality of RA. On one hand, it was reported that up to 30% replacement with recycled coarse aggregate (RCA) induces no substantial reduction in the compressive strength of the resulting concrete [18–20]. On the other hand, some researchers reported a significant reduction in the compressive strength of RAC prepared with a minimum of 30% RCA [21,22]. At full replacement with RCA, up to 30% loss in compressive strength was recorded in relation to concrete made entirely of NA [18,20,23]. This variation is mainly due to the fact that the compressive strength of concrete majorly depends on the quality of the paste and the interfacial transition zone [5].

Studies have also shown that the flexural strength is not adversely affected by the incorporation of RCA [18–20], however, a 100% replacement with RCA induced about 10% reduction [3,18]. Applying Eurocode 2 to RAC mix design, Wardeh et al. [12] noticed up to 20% loss in both flexural and tensile strengths of RAC produced using 100% substitution of natural coarse aggregate (NCA). According to the authors, the developed model gave closer results to the experimental results than those obtained using the equations given in Eurocode 2. Fathifazl et al. [5] also argued that the devastating effect of RA on the elastic modulus of RAC has not been salvaged by any known mix design technique except the equivalent mortar volume (EMV) approach. Thus, in a review carried out, Anike et al. [1] concluded that factors such as grade and composition of parent concrete, mixing method, content and moisture condition of RA, and presence of admixtures definitely influence the properties of RAC as reflected in the results available in literature.

With regard to packing density, mixtures of crushed aggregates are less compacted and have more voids due to the angularity of the particles compared to rounded ones [24]. A less dense packing produces a higher water-cement ratio, giving rise to a more porous paste [25]. In concrete technology, the interaction of the matrix which comprises of water, air and powder defined by particles smaller than 125µm [26], is imperative in filling the voids. This phenomenon improves the microscopic properties (strength or durability) of the concrete depending on a number of factors; including water-cement ratio, reactivity, particle shape and particle size distribution. To maintain a low water-cement ratio with proper homogenisation of the cement and filler, Moosberg-Bustnes et al. [25] pointed out that superplasticizer plays a key role. The authors maintain that superplasticizer has a greater efficiency in a denser particulate system than in a porous low-density system. This may be the reason why, upon the high demand of superplasticizer by 100% RA-concrete mixes to equal the workability of conventional concrete, there is still a need for improvement in the properties of the ensued RAC. Nonetheless, if the properties of RA are properly defined alongside a suitable mix design technique, concrete of good quality can be obtained.

The present study utilizes proper gradation and the hybrid form of RA to investigate the effect of mix design methods on the properties of RAC intended for structural uses. Overall, three different mix design techniques are investigated in this study, out of which, two are conventional methods and one is the EMV method proposed by Fathifazl et al.[5]. It should be noted that Fathifazl et al. [5] in their work, substituted recycled aggregate for coarse aggregate only. To the best of the present authors' knowledge, no work has been carried out for the replacement of both NCA and natural fine aggregate (NFA) in concrete prepared with the EMV method. This research has gone a step further to incorporate recycled fine aggregate (RFA) in addition to RCA for the production of RAC proportioned using this new technique. This is achieved by using the same ratio of replacement obtained from the design procedure of the EMV highlighted in the next section.

Therefore, this study aims to significantly reduce the amount of pressure on natural aggregates (coarse and fine). Of particular interest in this research is the amount of cement gain, to be offered by the investigated mix design methods, in quest for sustainable construction materials.

2. Theoretical Justification

In view of the challenges posed by RA, which have limited its applications, several studies have been carried out in the past to upgrade its performance in structural concrete. Mulder et al. [27] proposed the thermal process which involves the heating of concrete waste to a temperature of at least 700^{o}C. The authors believe that the separation of the individual components is attainable at this temperature. A set of other researchers recommended a chemical process by which the mortar adhering to the RA is expected to dissolve in the presence of phosphoric, sulphuric or hydrochloric acid solution [28,29]. Different moisture (or surface) condition of the RA prior to usage has also been advocated [7,30]. Other techniques are related to the concrete mix. The list herein includes: the adjustment of the water-cement ratio to improve compressive strength [31], alternative to normal mixing method [19,32], addition of admixtures such as superplasticizer, pozzolans and fibres [21,33–35], the EMV mix proportioning method [5], the particle packing method (PPM) of RAC mix design [15], and the compressible packing method (CPM) [36]. However, these methods have their ups and downs, at times quite laborious, energy intensive, expensive or even harmful to human and the environment.

In the present authors' opinion, since RA is a hybrid material composed of the residual mortar and natural virgin aggregates [37], the use of normal mix design method for RAC would assume RA a homogeneous material. Also, the suggestion in the literature to replace for NA using certain percentages (replacement by weight of 20, 25, 30, etc) of RA, is not an absolute solution to the associated shortcomings of RA, due to its variability in quality. Thus, the remedy lies in the proposition of the EMV mix design method which mainly advocates for two things:

(i) The recognition and treatment of RA as a two-phase material. This implies treating the dry mortar adhering to the RCA as part of the overall paste content of RAC thereby enhancing the quality of the concrete paste. This practice ensures equality of total volume of paste between RAC mix and the companion mix prepared entirely with NA.

(ii) The use of both RA and NA properties in determining the replacement level with RA as opposed to guesswork of using any replacement ratios suggested in the literature. RCA quality (which is dependent on the quality of the parent concrete) determines its paste content, and this in turn determines the replacement ratio of NCA.

Furthermore, opinions have been against the use of RFA in concrete production due to its associated workability issues engendered by abundant particles of dry mortar present in the recycled fines. This view could, among other reasons, be because of the tendency of agglomeration within such mix, creating more voids that will impair with the general quality of the concrete. But the work of superplasticizer in the matrix is to prevent and break down the agglomerates, reduce water demand by releasing water trapped between the agglomerates and to disperse the fine particles into the voids [24,25]. These phenomena are anticipated to have more impact in concrete containing RA (due to its hybrid nature) than that with NA. In which case, the loosely bounded dry mortar coating the surface of RCA is readily dissolved, thus the tiny particles acting as fillers in the matrix. It was also noticed in a while after sieving the concrete rubble into different size fractions stated below (Section 3.2), that a reasonable amount of tiny particle was present in the larger grades. Again, the proportion of RFA in the crushed concrete is doubled that of RCA. This follows that, not using RFA in concrete production will still put pressure on landfills. Based on these facts and the above hypothesis, the authors adapted to the integration of RFA as well as using the EMV design principles.

The provisions of the EMV technique involve series of mathematical formulations, however, the method can be realized in seven basic steps. The full details of the EMV mix design approach for RAC can be found in Fathifazl et al. [5], but the procedure has been summarised in the following steps, with an additional step due to the inclusion of RFA in the present investigation:

(1) Proportion the NAC based on any convenient conventional method;

(2) Check whether complete replacement of NCA with RCA is possible;

The condition for a complete replacement is that the calculated residual mortar content (RMC) must be greater than the actual value obtained as described in Section 3.3 of this paper. The maximum residual mortar content is given by:

$$RMC_{max}\% = \left(1 - V_{DR-NCA}^{NAC} \times \frac{S_b^{NCA}}{S_b^{RCA}}\right) \times 100 \qquad (1)$$

Where V_{DR-NCA}^{NAC} *is the dry-rodded volume of the NCA in NAC,* S_b^{NCA} *is the bulk specific gravity of NCA and* S_b^{RCA} *is the bulk specific gravity of RCA;*

(3) Check the minimum quantity of fresh NCA in RAC. This is given by;

$$R_{min} = 1 - \frac{(1-RMC)}{V_{DR-NCA}^{NAC}} \times \frac{S_b^{RCA}}{S_b^{NCA}} \quad (2)$$

To make up for the NCA in RAC mixes in comparison with NAC mixes, the volume of fresh NCA in RAC is assumed to be equivalent to the volume of the residual mortar. Thus,

$$R = 1 - (1 - RMC) \times \frac{S_b^{RCA}}{S_b^{NCA}} \quad (3)$$

Where R is the volume of fresh NCA in RAC;

(4) Calculate the required volume of RCA and NCA in RAC using the following expressions:

(i) $$V_{RCA}^{RAC} = V_{NCA}^{NAC} = \frac{W_{OD-NCA}^{NAC}}{S_b^{NCA} \times 1000} \quad (4a)$$

(ii) $$V_{NCA}^{RAC} = R \times V_{NCA}^{NAC} \quad (4b)$$

Where V_{RCA}^{RAC} and V_{NCA}^{RAC} are respectively the volume of RCA and NCA in RAC, V_{NCA}^{NAC} and W_{OD-NCA}^{NAC} are the volume of NCA in NAC and oven-dry weight of NCA in NAC, respectively;

(5) Calculate the required oven-dry weight of RCA and NCA in RAC from the following expressions:

(i) $$W_{OD-RCA}^{RAC} = V_{RCA}^{RAC} \times S_b^{RCA} \times 1000 \quad (5a)$$

(ii) $$W_{OD-NCA}^{RAC} = V_{NCA}^{RAC} \times S_b^{NCA} \times 1000 \quad (5b)$$

Where W_{OD-RCA}^{RAC} and W_{OD-NCA}^{RAC} are respectively the oven-dry weight of RCA and the oven-dry weight of NCA in RAC;

(6) Calculate the required quantity of fresh mortar (FM) and residual mortar (RM) in RAC

(i) $$V_{RM}^{RAC} = V_{RCA}^{RAC} \times \left[1 - (1 - RMC) \times \frac{S_b^{RCA}}{S_b^{NCA}}\right] \quad (6a)$$

(ii) $$V_{FM}^{RAC} = V_M^{NAC} - V_{RM}^{RAC} \quad (6b)$$

Note: $V_M^{NAC} = 1 - V_{RCA}^{RAC}$; V_{RM}^{RAC}, V_{FM}^{RAC} and V_M^{NAC} are volume of RM in RAC, volume of FM in RAC and volume of mortar in NAC, respectively;

(7) Calculate the required quantity of water, cement and NFA in RAC as follows:

$$W_W^{RAC} = W_W^{NAC} \times \frac{V_{FM}^{RAC}}{V_M^{NCA}} \quad (7a)$$

$$W_C^{RAC} = W_C^{NAC} \times \frac{V_{FM}^{RAC}}{V_M^{NCA}} \qquad (7b)$$

$$W_{OD-NFA}^{RAC} = W_{OD-NFA}^{NAC} \times \frac{V_{FM}^{RAC}}{V_M^{NCA}} \qquad (7c)$$

Where W_W^{RAC}, W_W^{NAC}, W_C^{RAC}, W_C^{NAC} and W_{OD-NFA}^{RAC} are weight of water in RAC, weight of water in NAC, weight of cement in RAC, weight of cement in NAC and weight of oven-dry NFA in RAC, respectively;

(8) Apply the same ratio of RCA and NCA obtained in step 5 to the quantity of NFA obtained in equation (7c) to get similar replacement ratio for the fine aggregates. According to Table 3, the ratio of RCA to NCA for the present research is 1.5:1, and this is also applicable to RFA and NFA.

3. Research Methodology

The motivation for this research was drawn from the work by Fathifazl et al. [5] and the recognition of the impact of well-graded aggregates in concrete. Consequently, sieve analysis of the aggregates was first conducted on the raw materials. Then, a representative fraction was obtained using the quartering method according to ASTM C702 [38] to determine the properties of the aggregates. Next, a total of four mixes were formulated with a target characteristic concrete strength of 40N/mm^2 at 28 days. The list includes the reference mix designated natural aggregate concrete (NAC), which consists of NA and designed using the conventional method. Two different mixes consisting entirely of RA, labelled recycled concrete aggregate concrete (RCAC); with one prepared using the absolute volume method described in the American Concrete Institute (ACI) standard [39] and the other designed with the Department of Environment (DoE) method according to the British Standard [40]. The rationale for this, is to identify the standard (ACI or DoE) that manages resources better without compromising strength at the same time.

Consequently, concrete was tested for early strength in compression at 7 days and the standard that gave a better result was adopted as the conventional method for NAC and RCAC. Finally, a mix in which both NA and RA are partially substituted were designed using the EMV approach and this mix is named blended aggregate concrete (BAC). Concretes were then produced accordingly, cured by water immersion and tested for density, compressive strength, tensile splitting strength and water absorption. The sequence of activities undertaken to achieve this research is given in Figure 1.

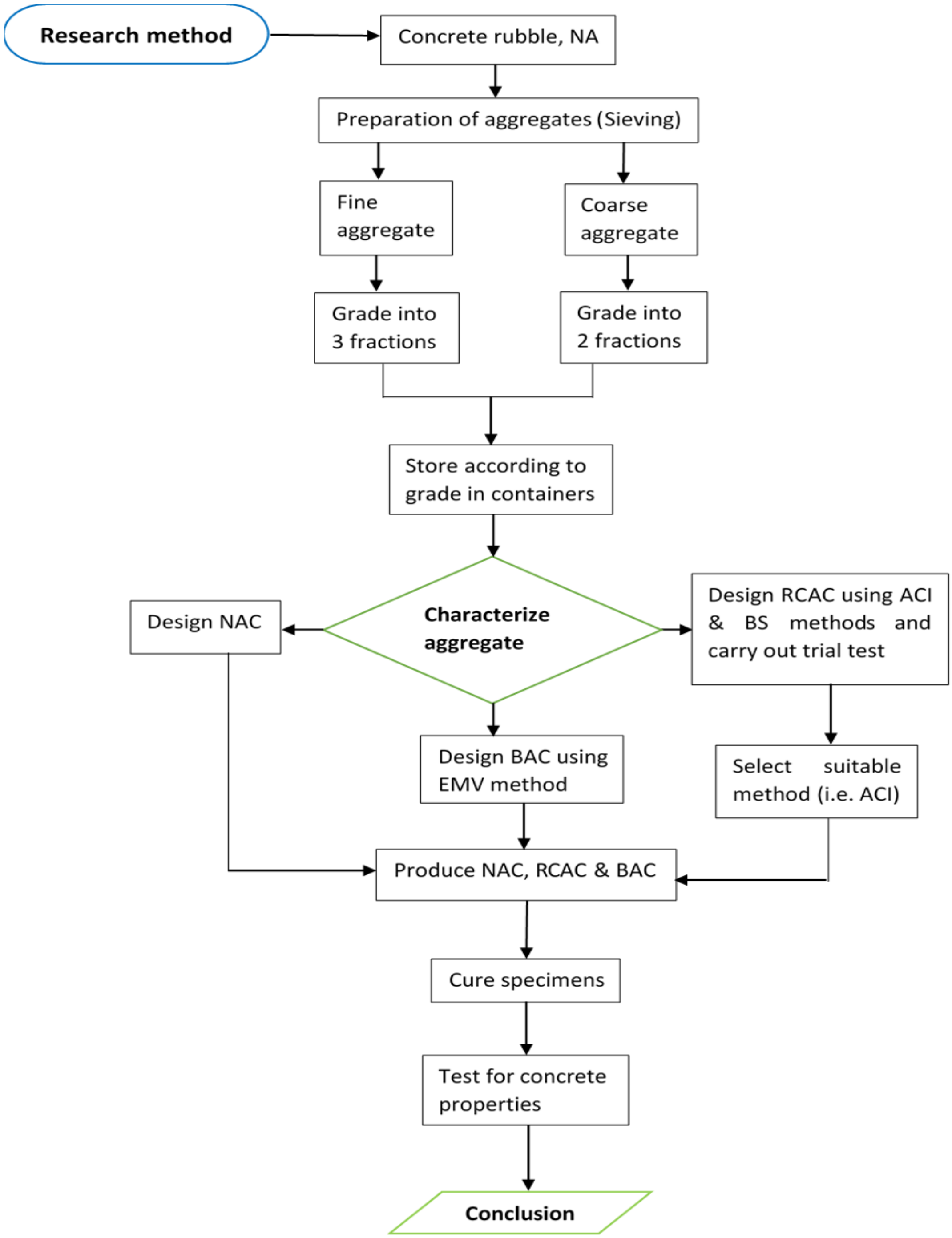

Figure 1: Research methodology flowchart

3.1 Materials

All materials used for this investigation, except for water, were supplied by Litecast HomeFloors Ltd., a precast concrete beam company located at Nuneaton, West Midlands, United Kingdom. The NA used is also the original aggregate in the concrete rubble and all concretes produced by the company have a day strength of approximately 40N/mm^2. The properties of fine and coarse aggregates used for the experiments are as shown in Table 1 and Table 2 respectively. CEMEX Rapid CEM I Portland cement which conforms to the European standard BS EN 197-1 [41] and Sika ViscoCrete 335 water reducer admixture that meets BS EN 934-2 [42] requirements, were used. Potable tap water was used for this study.

3.2 Grading of aggregates

The concrete rubble was first sieved by hand using standard sieves, to obtain the coarse aggregate and to remove the included impurities shown in Figure 2. The maximum size of the NCA is 14mm and this automatically regulated the size of its parallel RCA to 14mm. Hence, all aggregates in the range of 4.75 – 14.00mm were regarded as coarse aggregates for both NA and RA. On the other hand, those in the range of 0.075 – 4.75mm were considered as fine aggregates. For the purpose of fair comparison between the NA and RA, the aggregates were treated alike in terms of their gradation.

Table 1: Properties of fine aggregates

Aggregate type	Size fraction (mm)	Specific gravity			Absorption (%)	Fineness modulus
		OD	SSD	AP		
NFA	4.750 - 2.470	2.48	2.52	2.57	1.4	2.87
	2.470 - 0.570	2.57	2.60	2.65	1.1	
	0.570 - 0.075	2.62	2.63	2.66	0.6	
RFA	4.750 - 2.470	2.15	2.34	2.66	8.9	2.71
	2.470 - 0.570	1.96	2.20	2.57	12.1	
	0.570 - 0.075	1.78	2.10	2.62	18.1	

Note: NFA = natural fine aggregate, RFA = recycled fine aggregate; OD, SSD and AP are oven-dry, saturated surface-dry and apparent specific gravity respectively.

Table 2: Properties of coarse aggregates

Aggregate type	Size fraction (mm)	Specific gravity			Absorption (%)	Void (%)	Loose bulk density (kg/m^3)	Dry-rodded density (kg/m^3)	Residual mortar content (%)
		OD	SSD	AP					
NCA	4.75 - 10.00	2.60	2.63	2.67	0.9	41	1450	1543	-
	10.00 - 14.00	2.62	2.64	2.66	0.6	39	1479	1586	-

RCA	4.75 - 10.00	2.30	2.42	2.62	5.4	43	1207	1300	51.49
	10.00 - 14.00	2.30	2.42	2.61	5.1	44	1171	1293	51.97

Note: OD, SSD and AP are oven-dry, saturated surface-dry and apparent specific gravity respectively

The coarse aggregates were graded into two size range of 4.75 – 10.00mm and 10.00 – 14mm and were integrated in ratio 7:3 to produce concrete. Meanwhile, the fine aggregates were sieved through a set of wire mesh, in the order: 4.75 – 2.47mm, 2.47 – 0.57mm and 0.57 – 0.075mm and were combined in ratio 1:2:3 to achieve similar gradation as well as medium range fineness modulus. Moreover, a higher proportion of the smaller range fractions for both fine and coarse aggregates was adopted to enhance the packing density through filling of holes created by larger particles [25]. The gradation curves of both natural and recycled fine aggregates after the sieving process are shown in **Error! Reference source not found.**.

Figure 2: Impurities from a typical precast concrete rubble

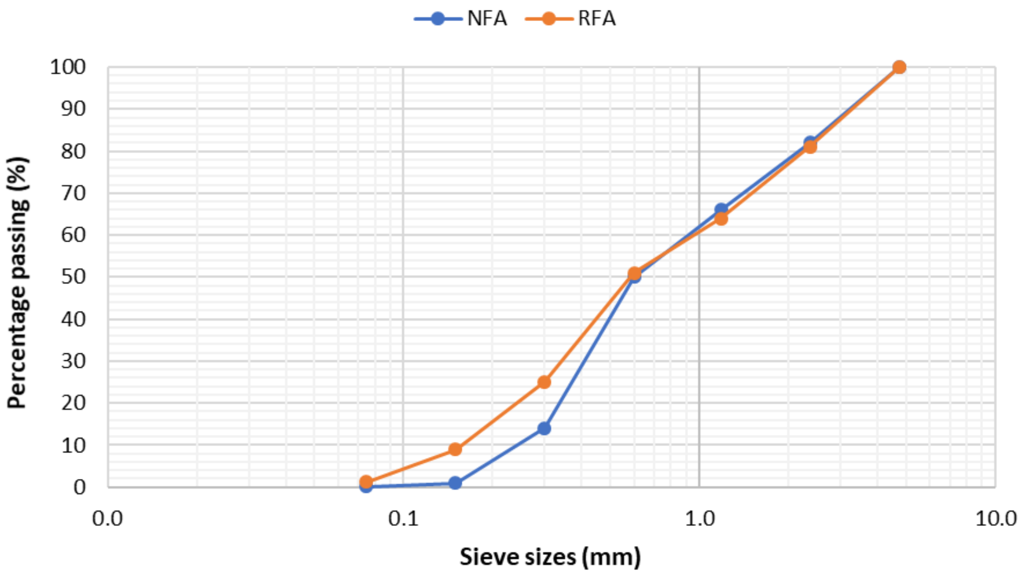

Figure 3: Gradation curves of NFA and RFA

3.3 Determination of mortar content of the RA

The amount of mortar present in the RA is required to adapt to the EMV mix design technique. A similar procedure highlighted in the work of Abbas *et al.* [8] was employed to determine the volume of mortar in the RCA as follows:

- The representative samples obtained using quartering method are oven-dried for 24 hours at a temperature of 105°C.
- The samples are completely immersed in a 26% (by weight) Sodium Sulphate solution for 24 hours.
- While still immersed in the solution, RA are subjected to freezing and thawing for five daily cycles at -17^{0}C (for 16 hours) and 80°C (for 8 hours) respectively. This condition is like that used in ASTM C672 [43] for scaling test.
- At the end of the last freezing and thawing cycle, the solution is drained, and the samples washed with tap water over a 4.75mm sieve.
- The washed samples are then oven-dried for 24 hours at a temperature of 105°C.
- Finally, the required masses (before and after treatment) are substituted in equation 8 to obtain the residual mortar content. That is;

$$\mathrm{RMC}(\%) = \frac{\mathrm{M_b} - \mathrm{M_a}}{\mathrm{M_b}} \qquad (8)$$

Where RMC is the mortar content (%), M_b is the mass of RA before treatment (g) and M_a is the mass of RA after treatment (g).

4. Experimental Program

The mix proportions of concrete constituents obtained from the adopted mix designs are given in Table 3. Trial mixes were performed to ensure that similar workability, measured in terms of the slump of fresh concrete, is maintained for all mixes. This was deemed appropriate due to workability issues associated with RA, especially when RFA is in use. The workability of the concrete samples was determined through a slump test in accordance with BS EN 12350-2 [44]. According to National Structural Concrete Specification (NSCS) [45], "Most structural concrete should be consistence class S3." Hence, this is the requirement for the slump test within the testing and concrete design. BS 8500-1:2015+A2 [46] underlines the dimensional parameters for specified slump class S3 as 90mm to 170mm.

The two-stage mixing approach (TSMA) proposed by Tam et al. [11] was employed for all mixes comprising of RA (that is, RCAC and BAC mixes), while the normal mixing method was used for the NAC mix. Mechanical mixer was used for the mixing process and immediately a consistent mixture was attained, the fresh concrete was tested for slump. After an approximate slump values have been established, concrete ingredients for five 100mm cubes, three 150mm cylinders and three 100mm cylinders were batched for each mix. The constituents were mixed as mentioned above and placed in the mould where they were compacted in two layers (for cubes) and three layers (for cylinders) with the aid of a vibrating table. Subsequently, the hardened specimens were removed from the mould after about 24 hours and transferred to the curing tank. Compressive strength test was conducted on each cube-specimen in accordance with BS EN 12390-3 [47] code of practice, after 7 days. Prior to the compression test, the density of the specimens was determined at same age using BS EN 12390-7 [48] standard. The tensile splitting strength and water absorption capacity tests were performed on 150mm and 100mm cylinders according to BS EN 12390-6 [49] and BS 1881-122 [50], respectively.

5. Results and Discussion

5.1 Mix design

A number of observations are noted in the outcome of the mix design shown in Table 3. First, although both NAC and RCAC are designed using the ACI standard with exactly the same water-cement ratio, the amount of aggregates required varied significantly. This is definitely as a result of the dry mortar present in the RA which raises its water absorption capacity as well as reduces its specific gravity. Secondly, the mix proportions reveal that the quantity of aggregates in RCAC mixes developed with the ACI and British standards are relatively the same. However, the latter requires an appreciably higher cement content. Thirdly, the design of RAC with the EMV guidelines greatly reduced the amount of cement needed, making it the most cost-effective method. Finally, the use of EMV specification increased the need for superplasticizer tremendously, to achieve similar range of slump values measured for the other mixes. This is in agreement with the findings of Fathifazl et al. [5]. Apart from improving the workability of concrete, the superplasticizer enhances the particles packing by dissolving the flocks and diffusing the fine particles in the mix, thus reducing wall effect between larger particles, then increasing strength [24,25].

Table 3: Mix proportions of concrete designed with both conventional and EMV methods

Mix ID	Design method	Mix Proportions (kg/m³)							w/c	Slump (mm)
		Water	Cement	NCA	RCA	NFA	RFA	SP		
NAC	ACI	213	507	856	0	707	0	1.27	0.42	110
RCAC	ACI	213	507	0	754	0	534	1.52	0.42	135
RCAC	DoE	240	570	0	769	0	576	1.03	0.42	160
BAC	EMV	153	364	493	754	203	305	7.28	0.42	170

SP = superplasticizer, w/c = water-cement ratio

5.2 Hardened density

The result of the 7 days hardened density of concrete specimens produced from the four mixes is presented in **Error! Reference source not found.**. Overall, the reference mix prepared with NA showed the highest value than its comparable mixes in which RA is partially or totally incorporated. This is expected, due to the presence of dry mortar, which is a porous and lightweight material, attached to the RA. The differences in the values obtained by comparing NAC with RCAC(ACI), RCAC(DoE) and BAC are 8.4%, 4.2% and 2.5%, respectively. However, the role of mix design method can be seen in the results herein presented. About 4% difference exists in the density of RCAC produced with ACI and DoE methods, in favour of the latter. This variation may be attributed to the slightly higher amount of aggregate resulting from the British method. It should be noted from Table 3, that the American system uses lesser quantity of cement (507kg per cubic metre of concrete) in relation to the DoE method (570kg per cubic metre of concrete).

On the other hand, the new mix design approach gave a remarkable result. The BAC mix proportioned with the EMV technique showed only an insignificant difference when its density is compared with that of NAC. Also, the BAC gave a higher density than the concretes of the other mixes containing RA irrespective of its lower cement content. Hence, RA has no devastating effect on the hardened density of concrete when the non-conventional EMV mix design mechanism is used.

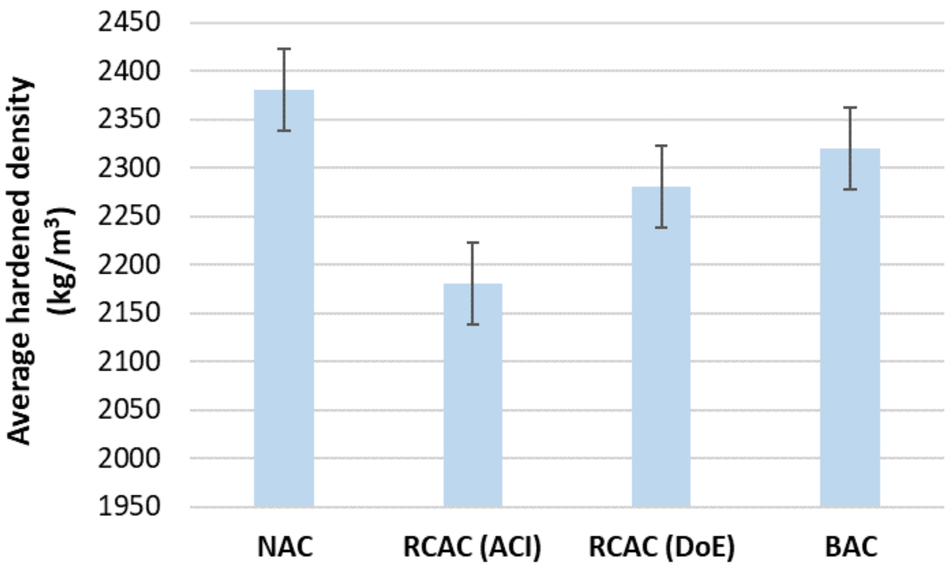

Figure 4: Hardened density of concrete for different mixes tested at 7 days

5.3 Compressive strength

The mean compressive strength of concretes resulting from different mixes presented in **Error! Reference source not found.**, shows that NAC has a higher strength than its equivalent RAC, regardless of the substitution level with RA. But the use of an alternative to the normal mix design method for RAC produced an impressive result. Even though the NAC is made of notably higher cement content compared with the BAC, only about 7% more strength than the BAC is observed. Also, the BAC shows a higher strength than RCAC(ACI) and RCAC(DoE) manufactured using the conventional style of mix design in excess of 18% and 27%, respectively. This can be explained from the perspectives of particles packing and impact of filler-material in concrete. Maximum packing density of granular materials engenders reduction of cement content [51]. Moosberg-Bustnes et al. [25] upheld that a looser but more homogeneous particles packing is aided by the presence of superplasticizer in the concrete matrix. The BAC mix has up to 80% and 86% higher dosage of superplasticizer than its comparable RAC mixes made from the ACI and DoE, respectively.

Likewise, in the granular skeleton optimization conducted by Wardeh et al. [12], it was observed that the packing density of RA is lower than that of NA due to the residual mortar. Therefore, since packing density improves concrete properties [15], the BAC mix with lesser amount of RA is expected to be denser, thus a higher performance.

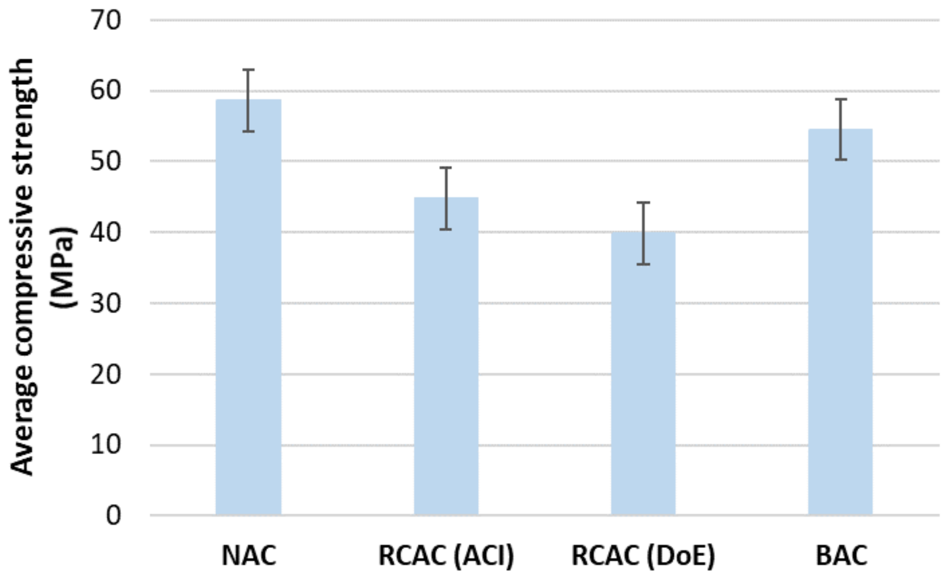

Figure 5: Compressive strength of concrete for different mixes tested at 7 days

Notice that the compressive strength of the RCAC designed and proportioned with the ACI approach is higher than that prepared using the British DoE method. This is opposed to the results observed in their density which depends mainly on the combined mass of the constituent materials. It is important to mention here that the ACI practice uses all the inherent properties of the aggregates obtained from their characterisation. This includes the relative density, water absorption capacity, bulk density and fineness modulus of the aggregates. Conversely, the DoE perspective uses only the relative density property and the percentage of fine aggregates passing 0.6mm sieve. All other features of the DoE method are based on existing graphs and tables obtained from experiments conducted on concretes of normal aggregates, neglecting the water absorption affinity of which has been described as the worst property of RA [52–54]. Consequently, the ACI mix design approach attracted up to 32% more superplasticizer than required by using the DoE guide, thereby producing a higher strength.

The compressive strength of the BAC obtained from the present study are compared with those of previous researchers who adopted the same mix design approach. Gupta and Bhatia [9] reported a higher compressive strength for concrete containing RA than the conventional concrete. Similar result was published by Fathifazl et al. [5] who recorded up to 13% more strength in favour of concrete produced with the EMV method. The current study observed a conflicting trend, and this is attributed to the inclusion of RFA. Also, it is important to note that the quality of RA for these comparative studies, differ significantly as reflected in their reported residual mortar contents.

5.4 Tensile Splitting Strength

Considering that the ACI mix design method offers a more cost-effective product from the compressive strength test, the authors reduced the number of mixes to three. **Error! Reference source not found.** gives the result of the tensile splitting strength of concretes from the three mixes tested at 28 days. Evidently, concretes consisting of RA (whether partially or completely replaced) show higher value for this concrete property than their comparable NAC. Similar result has been reported in the past [33,35,55,56] and some researchers have maintained that the tensile splitting strength of RAC does not depend mainly on quantity but quality of RA [33,57]. The effect of the EMV mix design method can be seen in **Error! Reference source not found.**, with up to 12% higher strength compared with the traditional method, even with NA.

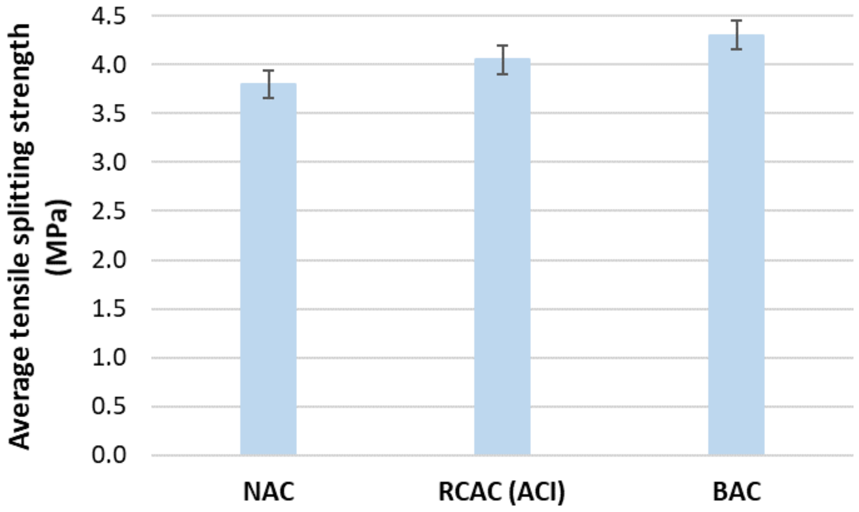

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Figure 6: Tensile splitting strength of concrete for different mixes tested at 28 days

5.5 Water Absorption Capacity

The water absorption capacity of concrete for the various mixes was studied at 28 days and the results are given in Table 4. As expected, NAC has a lower absorption capacity than RAC due to the dry mortar coating the surface of RA. However, this durability property of RAC is improved with the use of the EMV mix design approach. The RCAC prepared with 100% RA showed a higher affinity for water in excess of 39% than BAC manufactured using both natural and recycled aggregates. This shows that water absorption increases with replacement ratio of NA with RA and this is in agreement with the findings of previous studies [33,58].

Furthermore, considering some cumulative immersion periods up to 2 hours, the rate of water absorption of the concrete specimens was investigated at 28 days. Generally, from **Error! Reference source not found.**, the rate of absorption reduces with time. At all periods considered, the mixes comprising of RA showed a higher absorption rate than their corresponding NAC, irrespective of the mix design method. It can also be observed that the NAC is almost saturated after 2 hours, while the concretes of the other mixes still have the tendency for more absorption.

Table 4: Water absorption capacity of concrete for different mixes tested at 28 days

Mix ID	Specimen No.	Absorption (%)	Corrected absorption (%)	Average corrected absorption (%)
NAC	1	1.9	3.1	3.1

	2	1.9	3.1	
	3	1.9	3.1	
RCAC (ACI)	1	3.5	5.6	
	2	3.5	5.7	5.6
	3	3.3	5.4	
BAC	1	2.2	3.5	
	2	2.1	3.4	3.4
	3	2.1	3.4	

Finally, looking at the gradients of the RCAC and BAC plots in **Error! Reference source not found.**, both mixes show similar absorption rates. This may be as a result of equal amount of RCA in both mixes as shown in Table 3.

5.6 Relationship between density and compressive strength of RAC

Xiao et al. [59] conducted a comprehensive study on the mechanical properties of RAC and how they relate to each other. The authors compiled the results from various studies done globally and plotted them in graphs as required, to generate linear regression relationships between mechanical properties of hardened concrete. According to them, the relationship between density and compressive strength of RAC is expressed as:

$$f_{cu} = 0.069\rho - 116.1 \qquad (9)$$

Where f_{cu} and ρ are cube compressive strength and density of concrete, respectively. This formula has been applied to the results of this study having determined the experimental characteristic strength of concrete assuming a 5% defective level. Note that the relationship in equation 9 was developed using the results of concrete cubes tested at the 28 day and of compressive strength in the range of 15 – 55MPa. So, the expression must have been a combine effect of different standards across the globe. Table 5 shows that the predicted model underestimated the ACI and EMV methods by 18% and 15% respectively.

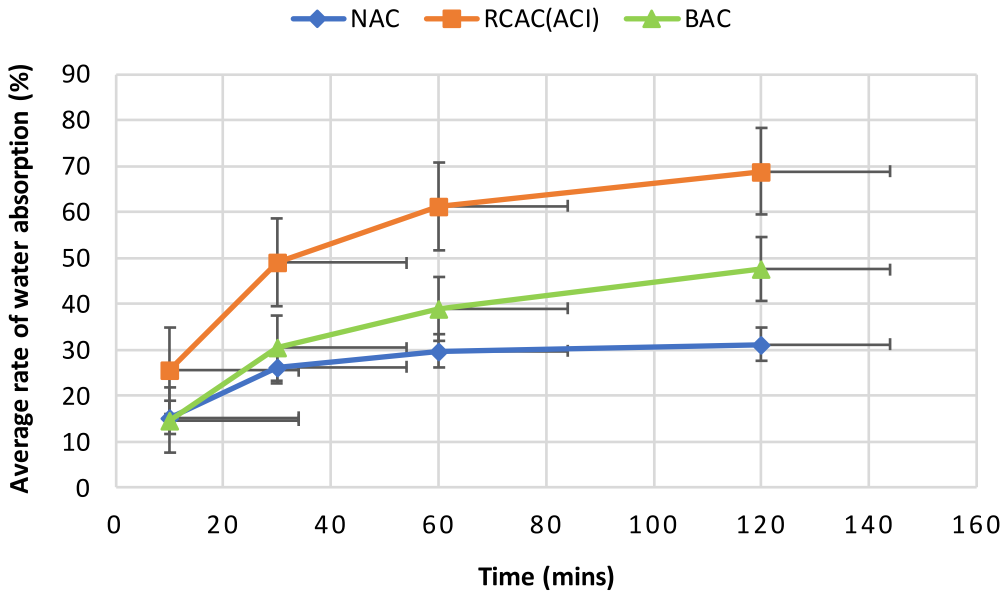

Figure 7: Rate of water absorption of concrete for different mixes tested at 28 days

Table 5: Comparison of predicted and experimental compressive strength of RAC produced using conventional and EMV methods

Design method	Density (kg/m^3)	Compressive strength (MPa)		STD§	Pred./Exp.
		Predicted	Experimental		
ACI	2180	34.3	41.5	2.04	0.82
DoE	2280	41.0	38.8	1.76	1.06
EMV	2320	44.0	51.6	0.58	0.85

§ = the standard deviation of the compressive strength of five cubes

6. Conclusion

This work presented an experimental study carried out to evaluate the effects of conventional and unconventional mixture design methods on recycled aggregate concrete (RAC). The recommendations by the American Concrete Institute (ACI) and the Department of Environment (DoE) are the conventional methods investigated, while the unconventional one dubbed "Equivalent mortar volume (EMV)" was developed by Fathifazl et al. [5]. Based on the findings of the investigation, the following conclusions are drawn:

(i) The RAC mixes proportioned with the ACI and DoE methods required more cement content (in excess of 143 and 206*kg* per m^3 of concrete respectively) compared to that proportioned using the EMV mix design method. More importantly, the reference mix made entirely of natural virgin aggregate and designed with the orthodox method, also used cement in excess of 143*kg* per m^3 of concrete in comparison to the EMV mix.

(ii) The EMV method requires a higher amount of workability-inducing reagent to match the slump value of RAC produced with the conventional mix design methods. It should be noted however, that the presence of the admixture improves particles packing which subsequently increases strength.

(iii) The hardened density of RAC mix designed using the normal practice is significantly lower than that prepared using the EMV recommendations. Comparatively, the DoE guidelines offers a denser RAC than its corresponding ACI standard. This is attributed to a higher aggregate content in the mix resulting from the former.

(iv) Similarly, the RAC mix proportioned with the EMV approach showed a superior compressive strength than those proportioned with its parallel ACI and DoE approaches. However, analogous to the density, the compressive strength of RAC produced using the ACI principles is slightly greater than that of DoE mixes. This is because compressive strength is dependent on quality of the paste unlike density that depends on the overall mass of the combining ingredients.

(v) All RAC mix gave a higher tensile splitting strength than their companion NAC mix. Again, the RAC mix from the EMV provisions performed better than that of ACI guide in terms of tensile splitting strength.

(vi) The water absorption capacity of RAC mixes (at all level of substitution with RA) is higher than that of its comparable NAC mix. Nevertheless, the use of an alternative to normal mix design method enhanced this property of RAC.

5.1 Recommendation

The authors hereby make following recommendations:

- The DoE mix design method should be reviewed and amended appropriately before adopting it for the production of RAC. This can be achieved by finding a way to incorporate all properties of RA, especially its water absorption capacity, into the RAC mix design rather than relying on curves and tables of value obtained from experiments performed with NA.

- Researchers should carry out more studies on variety of RA using the EMV mix design provisions. It is only by promoting this method which has been proven efficient in this research, that the world at large could unanimously agree to its endorsement.

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Conflicts of interest

The authors declare that they have no conflict of interest.

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